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ARL 17

THE LIMITING DETECTIVITY OF OPTICAL AMPLIFYING EQUIPMENT

R. K. H. Gebel
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APRIL 1961

AERONAUTICAL RESEARCH LABORATORY
OFFICE OF AEROSPACE RESEARCH
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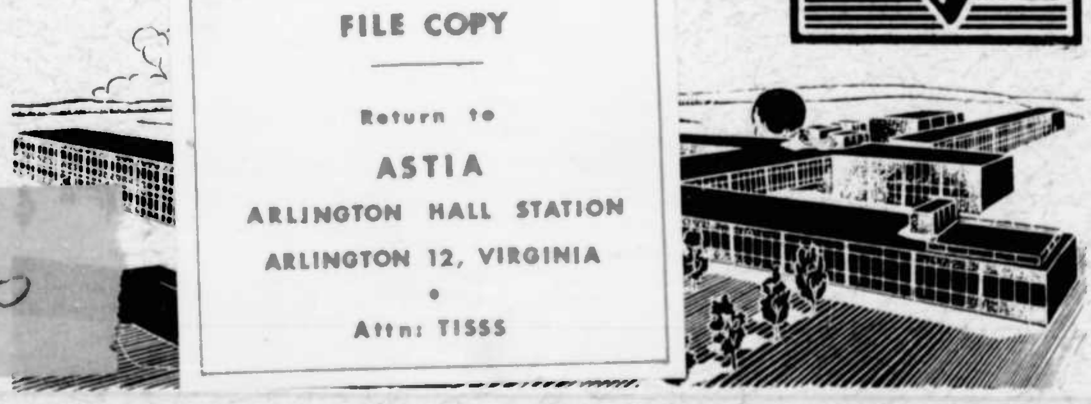

NOTICES

ARL 17

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Project 7072
Task 70827

AERONAUTICAL RESEARCH LABORATORY
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
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FOREWORD

This technical documentary report was prepared by the Solid State Physics Research Branch, Aeronautical Research Laboratory, under Project 7072, "Research on the Quantum Nature of Light", Task 70827, "Light Amplification", Mr. R. K. H. Gebel was the task scientist.

The authors wish to express their gratitude to Wittenberg University, Springfield, Ohio, for use of their telescope; to Dr. Lloyd R. Wylie, Professor of Astronomy at Wittenberg University for consultation; and, to the members of the technical team engaged in the work at Wittenberg, Mr. Heinrich Bost, Mr. Roy Hayslett, and Mr. Harry Beck. Also, to Mr. Hayslett appreciation is expressed for his assistance in preparing this technical report.

This technical documentary report supersedes WADC TN 59-405, dated December 1959.

ABSTRACT

The limits in the ability to produce photographic recordings for visual detection of very faint celestial bodies in the presence of the sky background by using conventional photography and by employing optical amplification with contrast enhancement and high capacity storage target plates are investigated and compared in this paper. Equations are appended which show the effects of the different variables involved for three types of imaging systems: the conventional photographic system, the image-converter, and the closed circuit television type of optical amplifier. In this technical report, the last named system is found superior to the two other systems.

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LIST OF SYMBOLS

q = Number of quanta arriving from celestial object per mm^2 sec on telescope (λ=415-670 m ; 6000°K)

M = Apparent magnitude number of celestial body

Q'_b = Number of quanta arriving from background radiation per mm^2 sec in the focal plane

D = Diameter of telescope objective (mm)

f = Focal length of objective (mm)

η = Transmission efficiency of telescope

B = Brightness of sky in foot lamberts

t = Time of exposure (seconds)

Q = Number of quanta from celestial object striking photographic emulsion or photocathode per sec

K'' = Number of resolution elements of photosensor covered by image of celestial body as result of diffraction and scintillations.

R = Number of resolution elements of photo-sensor per mm^2

r = Ratio of celestial body to background intensities of radiation required for detection = $QR/(Q'_b K'')$

M_l = Threshold celestial object apparent magnitude, assuming no failure of photographic reciprocity, perfect tracking and optimum exposure time available

η_c = Average ratio of electrons emitted to quanta received on photocathode

I = Number of dark current electrons per second and mm^2

BASIC EQUATIONS

$$(0) \qquad q = \frac{2.71 \cdot 10^4}{2.512^M} \left[\frac{\text{Quanta}}{\text{mm}^2\,\text{sec}}\right]$$

$$(1) \qquad Q'_b = 2.4 \cdot 10^{10} B \left(\frac{D^2}{f^2}\right) \eta \left[\frac{\text{Quanta}}{\text{mm}^2\,\text{sec}}\right]$$

PHOTOGRAPHY

$$(2P) \qquad Qt = \frac{2.13 \cdot 10^4}{2.512^M} D^2 \eta t \left[\text{Quanta}\right]$$

$$(3P) \qquad \frac{Qt}{K''} = r \frac{Q'_b t}{R} \left[\text{Quanta}\right]$$

$$(4P) \qquad M_l = 2.5 \log \left(\frac{8.9 \cdot 10^{-7} R f^2}{B r K''}\right)$$

$$= 2.5 \log \frac{A_l}{B} \; ; \; A_l = \frac{8.9 \cdot 10^{-7} R f^2}{r K''}$$

OPTICAL AMPLIFICATION

$$(2Am) \qquad Q \eta_c t = \frac{2.13 \cdot 10^4}{2.512^M} D^2 \eta \eta_c t \left[\text{Electrons}\right]$$

$$(3Am) \qquad \frac{Q \eta_c t}{K''} = r' \left[\frac{(Q'_b \eta_c + I) t}{R}\right]^{\frac{1}{2}} \left[\text{Electrons}\right]$$

r' = Ratio between the average numbers of electrons caused by the radiation from the celestial body and the square root of the average number of electrons corresponding to sky background plus dark current, giving a reasonable probability of detection of the celestial body.

$$(4Am)\quad M_1 = 2.5 \log \frac{2.13 \cdot 10^4 D^2 \eta \eta_c R^{\frac{1}{2}} t^{\frac{1}{2}}}{K'' r' \left[2.4 \cdot 10^{10} B \left(\frac{D}{f}\right)^2 \eta \eta_c + 1\right]^{\frac{1}{2}}}$$

$$= 2.5 \log \left[\frac{A_2}{(A_3 B + 1)^{\frac{1}{2}}} \, t^{\frac{1}{2}}\right]$$

$$A_2 = \frac{2.13 \cdot 10^4 D^2 \eta \eta_c R^{\frac{1}{2}}}{K'' r'}$$

$$A_3 = 2.4 \cdot 10^{10} \left(\frac{D}{f}\right)^2 \eta \eta_c$$

In the preceding equations it is assumed that the image of the celestial object either as a result of diffraction and/or scintillations covers at least one element of resolution.

INTRODUCTION

Research and developments in electronic imaging and in light intensification during the past few years have advanced extensively (Refs 6, 8). It appears worthwhile at this time to compare different kinds of imaging systems, which can be used to obtain astronomical photographs (Refs 9, 16, 17, 19, 22, 23).

The ability to detect differences in brightness, important for the detection of celestial bodies in the presence of the sky background, we shall call "contrast detectivity". An efficient imaging system must have in addition to high sensitivity, the capability of recording "very small" differences in brightness so that a celestial body whose image has a brightness comparable to that of the sky background can be detected. High sensitivity, which determines the necessary exposure time, is important for the detection of very faint celestial bodies or when working with a telescope having a small aperture. Such faint celestial bodies are normally recorded only with telescopes of large diameter, like the 200-inch diameter telescope at Mt. Palomar (Ref 26). A small telescope would require an exposure time that is too long to permit accurate tracking of a celestial body and the quantum efficiency of the photographic emulsion* is reduced by failure of the reciprocity law when the rate of arrival of quanta of light is very low.

The limit of contrast detectivity is ultimately determined by the irregular statistical variations in the total number of quanta collected on various resolution areas of the photosensor, plus the irregular statistical variations in number of electrons emitted by the photocathode and/or plus the irregular statistical variations in the number of developed grains which can be counted, observed, or used for reproduction of the information stored in the photographic emulsion (Ref. 1). In this report we shall treat the limits of contrast detectivity only, assuming that the devices which are compared here possess sufficient sensitivity for the task at hand and will neglect the failure of the reciprocity law (applicable only to the photographic process).

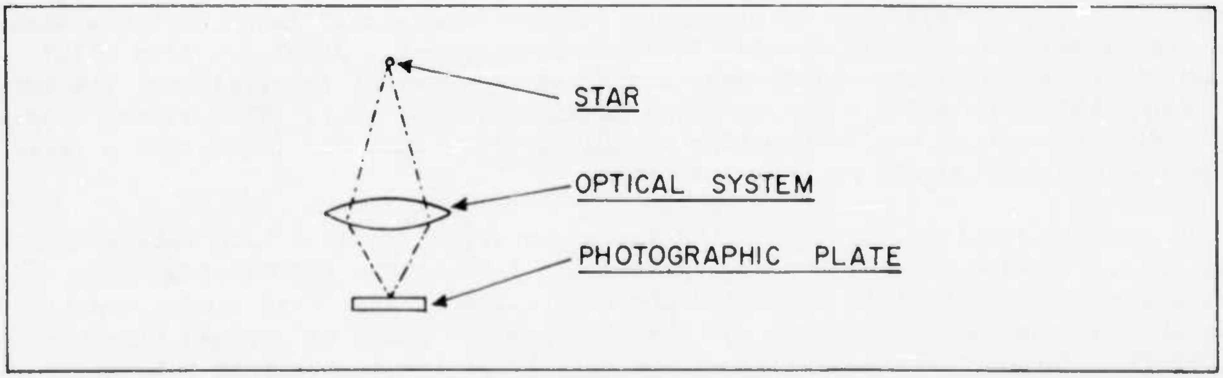

Figure 1. Conventional Photography

*The commonly used phrase "photographic emulsion" should be called "photographic gel" for scientific accuracy.

CLASSES OF IMAGING EQUIPMENT

The principal means for obtaining astronomical photographs may be divided into three groups as follows: conventional photography (Figure 1); systems in which the light collected by the telescope is intensified by using one or more image converter stages between it and the photographic emulsion (Figure 2) (Refs. 16, 17, 20); and systems in which the light is intensified and the contrast is enhanced by employing a closed circuit television chain with the telescope, and photographing the image that is produced on the cathode ray tube screen (Figure 3) (Refs. 5, 11, 12, 13, 14, 15, 23, 25).

In Figure 2, the image converter system, the image is focused onto a photocathode, each small area of which emits electrons in a number substantially proportional to the amount of light focused on it, usually on the order of one electron for each 10 to 20 quanta of visible light. The energy for the intensification is gained by accelerating these electrons in an electrostatic field, and imaging is accomplished by an electrostatic or magnetic lens (not shown in the sketch).

In the simplest tube arrangement of this system the electrons strike the reproducing phosphor screen directly (Figure 2a). The electron absorption and resultant excitation of the phosphor may produce an emission of more than 500 quanta of light for each electron absorbed; the number depends on the accelerating potential applied, which may be 10,000 to 30,000 volts. The image is then photographed.

To obtain higher intensification several image converter tubes may be cascaded, the image from the phosphor of one tube being focused on the photocathode of the next by a lens (Figure 2b).The transfer of the image between tubes and to the photographic emulsion may be made alternately by fiber optics.

High intensification may also be achieved by placing one, or several, intensifier screens between the photocathode and the final phosphor from which the image of the celestial body is photographed. Such an intensifier screen may consist, for example, of a phosphor and a contiguous photocathode (Figure 2c) (Ref. 24). Under the influence of the light from the phosphor, the photocathode emits electrons, which in turn are accelerated to produce a further intensified image by bombarding the next intensifier screen, or the final phosphor screen. An alternative solution for multiplying the flux of electrons is the use of a thin film structure, the transmission-secondary emission electron image multiplier (Ref. 28). The primary accelerated electrons which strike one side of such a film cause the release of a larger number of secondary electrons from the other.

In another possible version of the image converter system a thin vacuum-tight metal foil, called a Lenard window, replaces the final image reproducing phosphor and the glass on which it is deposited (Refs. 3, 4, 18, 27). This window constitutes part of the vacuum envelope and the photographic plate is pressed directly against it. The accelerated electrons are able to penetrate the thin foil and bombard the photographic emulsion which is outside the vacuum.

In cases where high velocity electrons, instead of light, produce the latent photographic image, the photographic emulsions available, for example, Kodak NTB III, may have grains with an average projected diameter as small as 0.2μ.

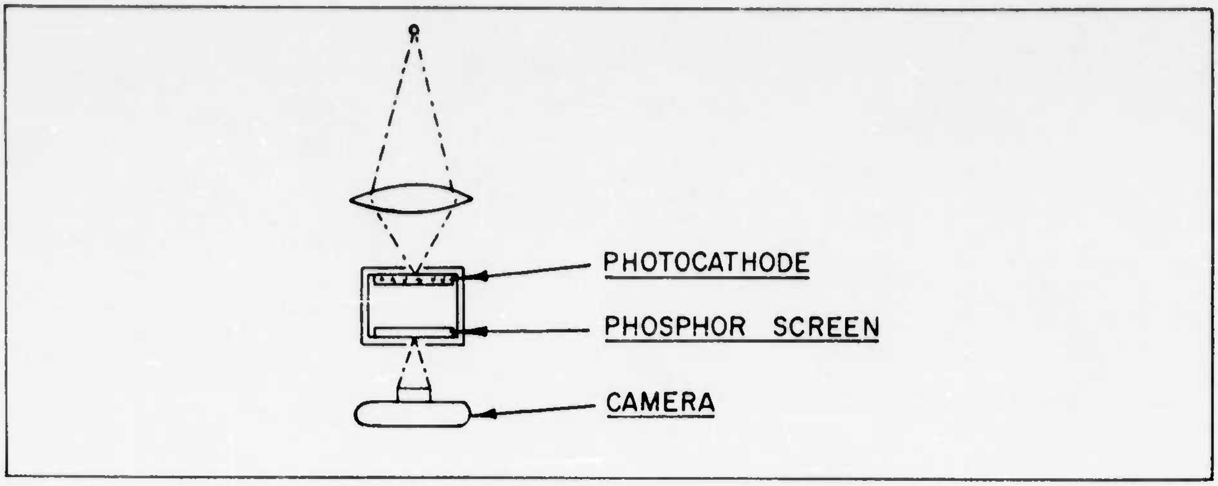

Figure 2a. The Basic Image-Converter System

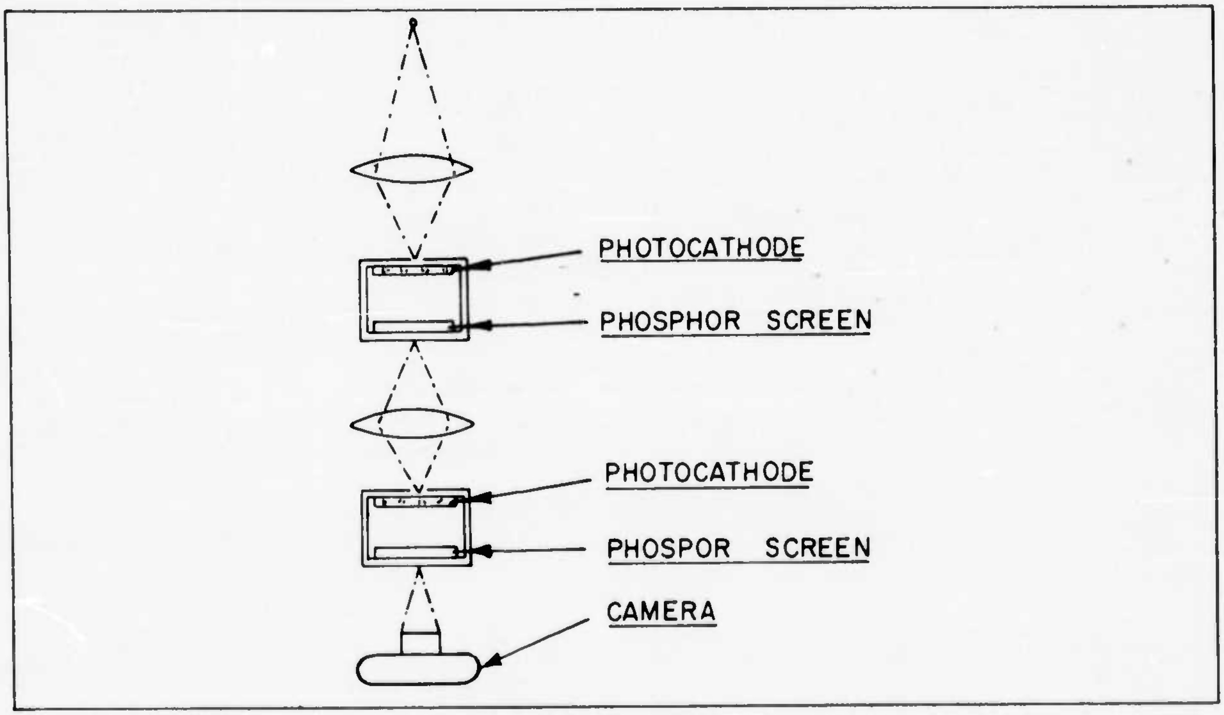

Figure 2b. The Image-Converter System Optically Cascaded

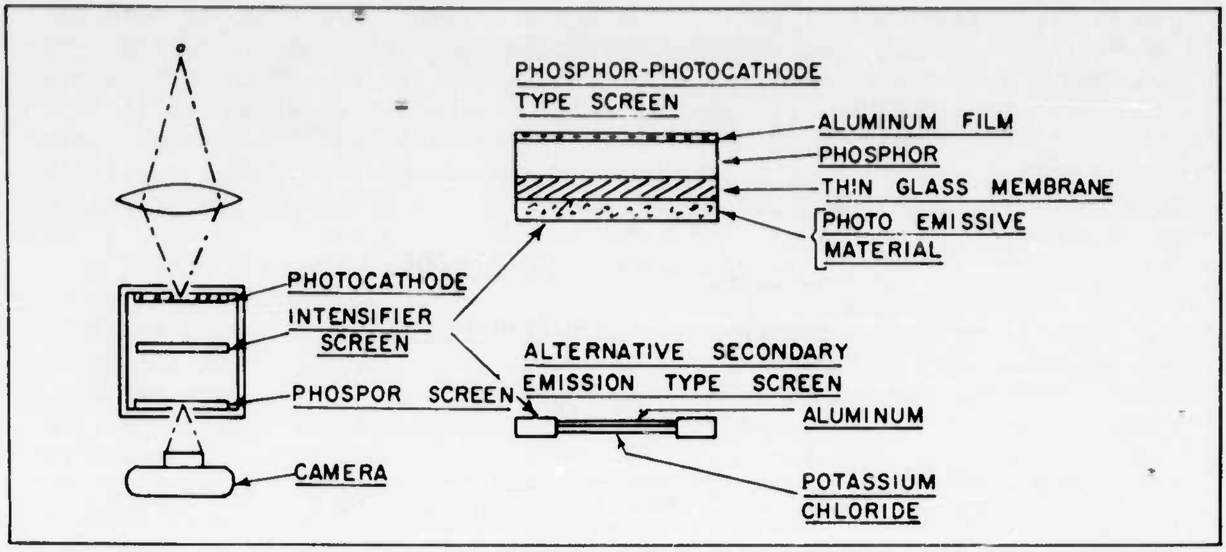

Figure 2c. The Image-Converter System Electronically Cascaded

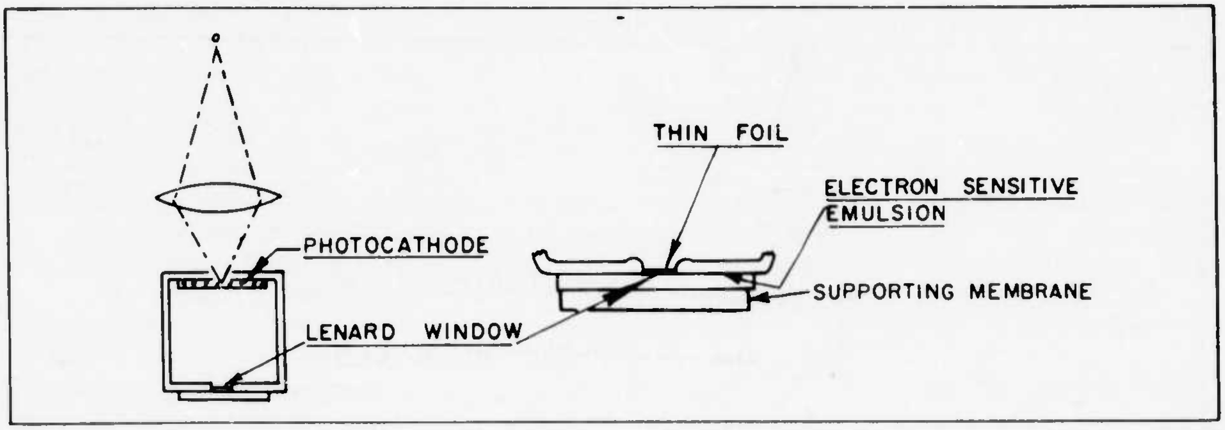

Figure 2d. The Image-Converter System with Lenard Window

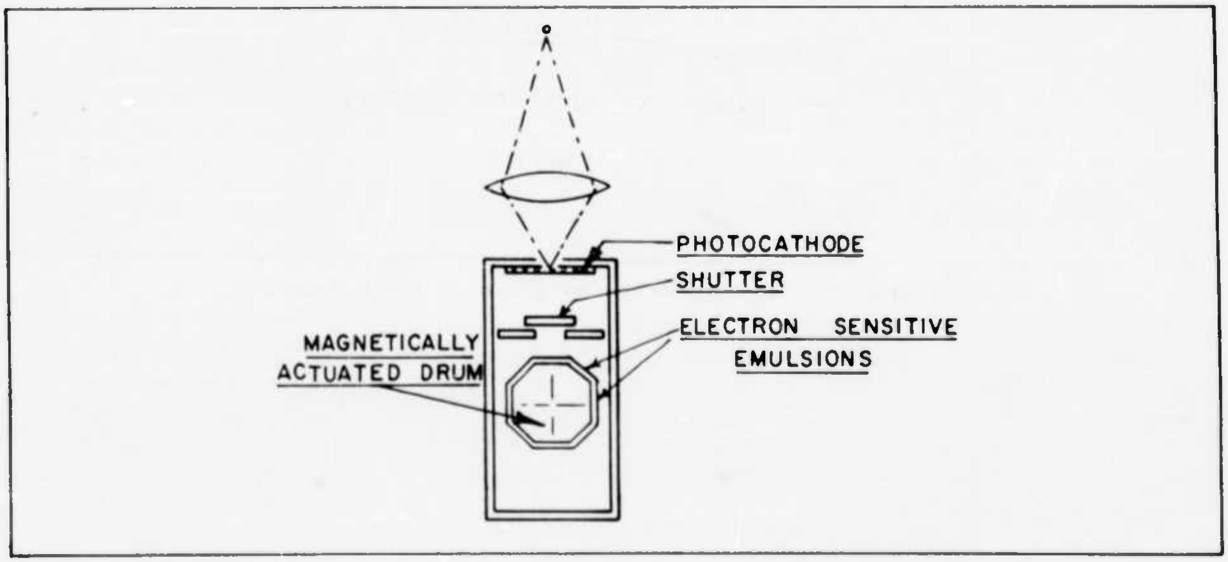

Figure 2e. Schematic of the Electronic Camera Designed by Prof. André Lallemand

The most advanced system employing an image converter type tube has been developed by Prof. André Lallemand of the Observatoire de Paris (Refs. 21, 22). Several photographic plates are placed on a drum within the vacuum of the tube where the electron sensitive photographic emulsion of each successive plate, as it is moved into position, can be directly bombarded by the accelerated electrons coming from the photocathode. With this system Prof. Lallemand has attained a resolution of 70 lines/per mm and has been able to record the impact of a single electron on the electron sensitive photographic emulsion.

Figure 3a shows the block schematic of a light amplifier of the closed circuit television chain type using the image orthicon principle in its scanning section. Here, the image of the celestial body is focused on the photocathode of the pickup tube and the optical image converted into an electron image. After acceleration and intensification the electrons produce an electrically positive charge pattern on the target plate. The scanning beam scans this charge pattern and converts it into a time-sequential video type signal. This signal is modified by using a threshold limiting circuit, an amplitude limiting circuit, and a contrast enhancement circuit, filtered to remove certain unwanted signals, amplified by the video amplifier, and, finally, used for modulation of the electron beam of a cathode ray tube. An electron beam scans the phosphor of this cathode ray tube in synchronism with the scanning beam in the pickup tube. The image of the celestial body that is reproduced on the phosphor screen of the cathode ray tube may then be photographed by conventional still or motion picture camera.

At present, the most sensitive pickup tubes are of the image orthicon type, but other television pickup tubes are also used successfully, for example, the C.P.S. Emitron (Ref. 23). With a conventional image orthicon, the noise in the scanning beam limits the low-light-level performance (Ref. 9). This limitation may be overcome by placing one or more image converter type light-intensifier tubes between the telescope and the photocathode of the image orthicon. Another solution is shown in Figures 3b and c which consist of schematics of the existing single and double stage intensifier image orthicons. In these tubes, up to three image converter stages have been built directly into the same envelope with an image orthicon; the phosphor screen of the last intensifier is contiguous to the photocathode of the image section of the image orthicon.

The low light level performance of a well constructed double stage intensifier image orthicon is limited mostly by the irregular statistical variations of the dark current of the first photocathode of the intensifier arrangement, and the statistical irregular variations in the conversion of the energy of light into electrons since the intensification is adequate to overcome the noise of the scanning beam. At light levels where these limiting fluctuations become visible, the resolution is determined by quantum mechanics, i.e., during the scan time, the smallest resolvable areas of the photocathode collect such a small average number of quanta of light that these irregular statistical variations determine the effective resolution. At light levels where the number of quanta of light available are adequate, well built image orthicon chains are able, at present, to achieve approximately 800 television lines per image without intensifiers and 350 lines with a double stage intensifier; however, since the telescopic image may be optically magnified before it reaches the pickup tube, this low resolution is not too important (Ref. 10).

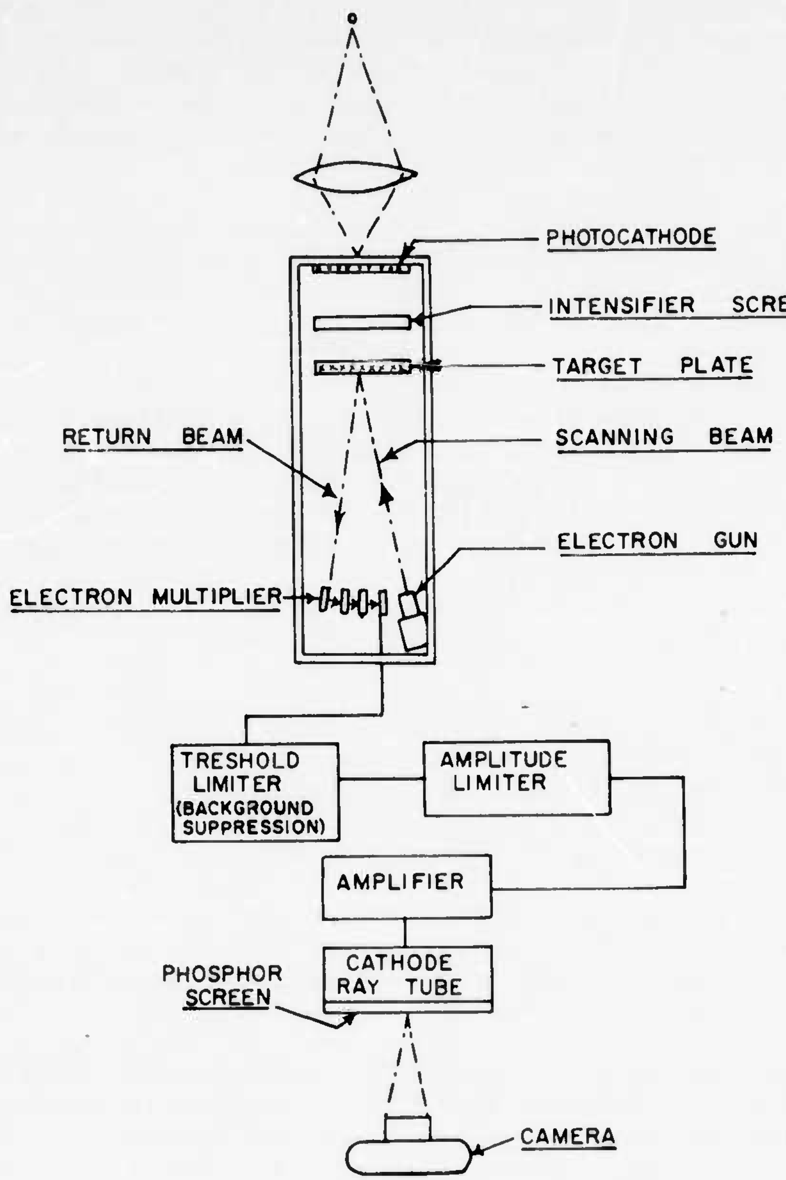

Figure 3a. Schematic of Television-Type Light-Intensifying Recording System

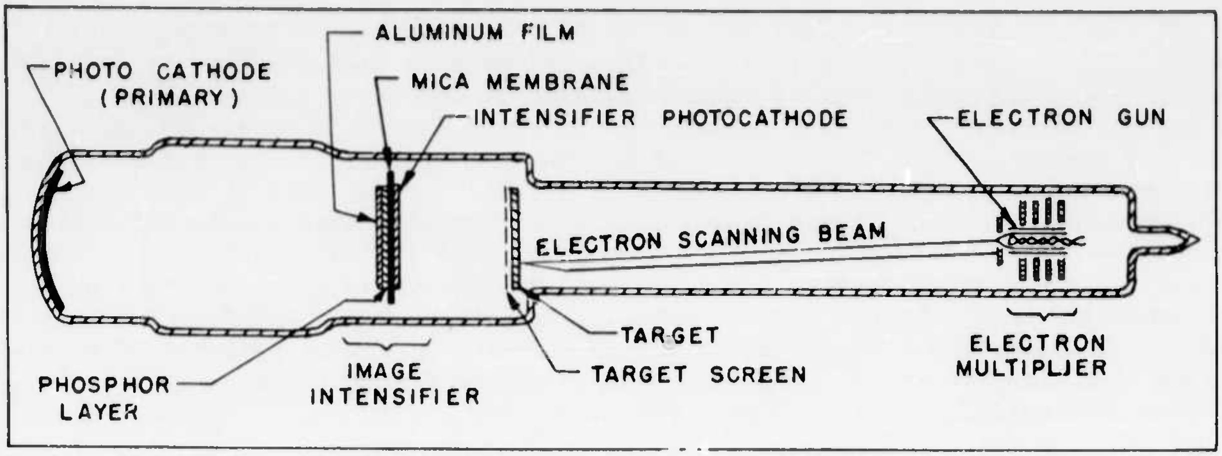

Figure 3b. Single Stage Intensifier Image Orthicon

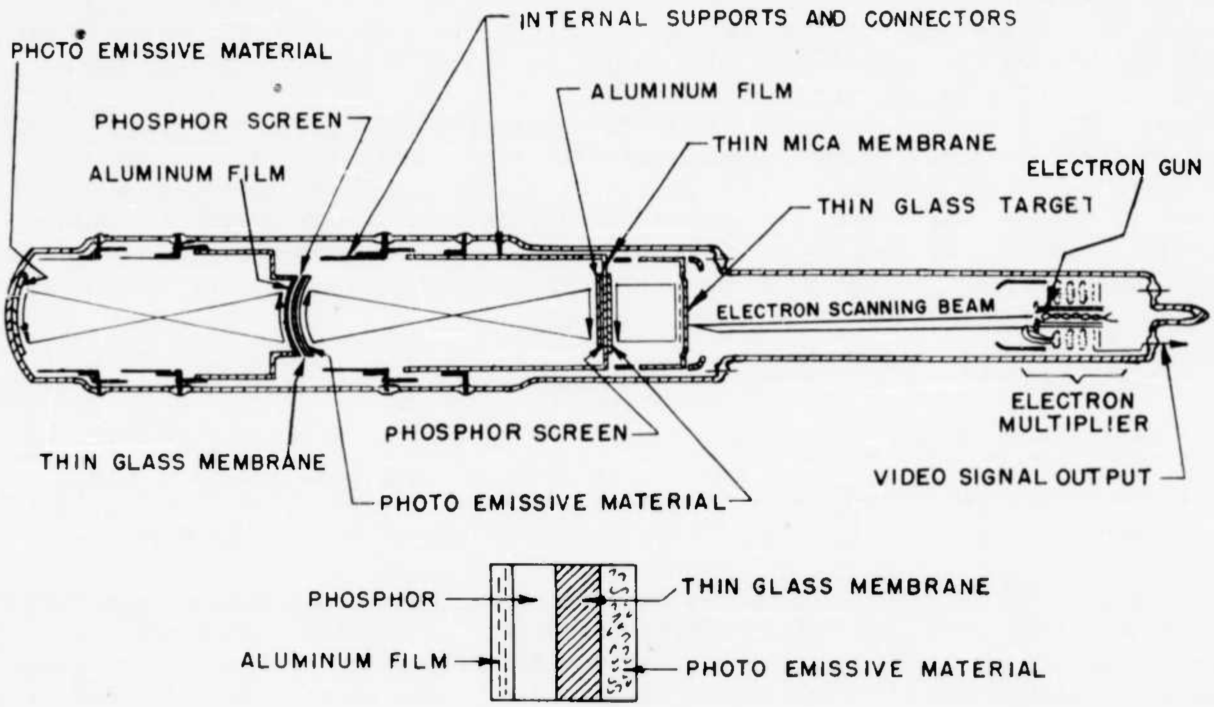

Figure 3c. Two Stage Intensifier Image Orthicon

The generation of the time sequential signal by the scanning beam of the image orthicon occurs at a thin glass plate referred to as the target or storage plate. The electrons coming from the preceding photocathode and impinging on the target plate produce secondary emission of a larger number of electrons, leaving a positive charge pattern. If the target plate has a high enough lateral electrical resistance, the charge can be collected and stored for some time without noticeable loss in resolution in the image. Since the target plate is only a few microns thick, the charge is able, during each scanning cycle, to diffuse from the side exposed to the electron image to the scanned side. Electrons from the scanning beam are deposited on the target plate, neutralizing this charge. The scanning beam is thus modulated by the information which was stored on the target plate and is directed to an electron multiplier; the output signal from this multiplier is fed into the video amplifier for further amplification.

It is extremely difficult by any other arrangement to equal the gain in light intensification and the contrast enhancement possible with the closed circuit television type of equipment. Experimental systems have been built by the Aeronautical Research Laboratory (Ref. 6) providing useful intensification from a light flux of $3 \cdot 10^{-8}$ foot candles on the photocathode of the pickup tube to a brightness of 30 foot lamberts on the cathode ray tube screen using a 1/30 second exposure time. These closed circuit television chains had a resolution of 100 television lines. At least five stages would be necessary to equal this intensification with cascaded image converter tubes. These systems have the additional advantages of permitting transmission of the signal by wire or broadcast, simultaneous reproduction on any number of cathode ray tubes, and direct display of even the faintest detectable celestial body in daytime light surroundings, without the inconvenience of an eye piece, (Ref. 6, 12). Other advantages of this type of equipment will be discussed in the section entitled "Image Converter System".

THE PHOTOGRAPHIC SYSTEM

Certain relationships among the contrast detecting capabilities of these three types of imaging equipment may be expressed by equations derived on the basis of the ability of each type to detect a faint celestial body in the presence of varying amounts of background. These relations may be derived as follows.

The rate of arrival at the Earth's surface of light quanta from a celestial body of apparent magnitude M (neglecting losses in the Earth's atmosphere) is given by Eq (0) (Ref. 8). Equation (1) gives the rate of arrival of light quanta from a sky background of brightness B at the focal plane of a telescope, (Ref. 9) and equation 2P derived from Eq (0) , the number of light quanta from a celestial body that is focused into an image by a telescope in a given time.

The light flux is expressed in quanta rather than in conventionel light units because the limitation in detecting faint celestial bodies in statistical considerations based on the quantum nature of light. Use of conventional units would lead to incorrect conclusions at the lowest light levels. For example, computation will show that the light from a 22nd apparent magnitude celestial body falling on a lens having a 5-inch diameter and an assumed transmission efficiency of 50 percent yeilds a light flux in the focal plane of 3×10^{-16} lumen. For a 1-second exposure this indicates the collection of only three tenths of a quantum of light when, actually, a quantum constitutes a discrete quantity of light which can arrive only as a complete entity.

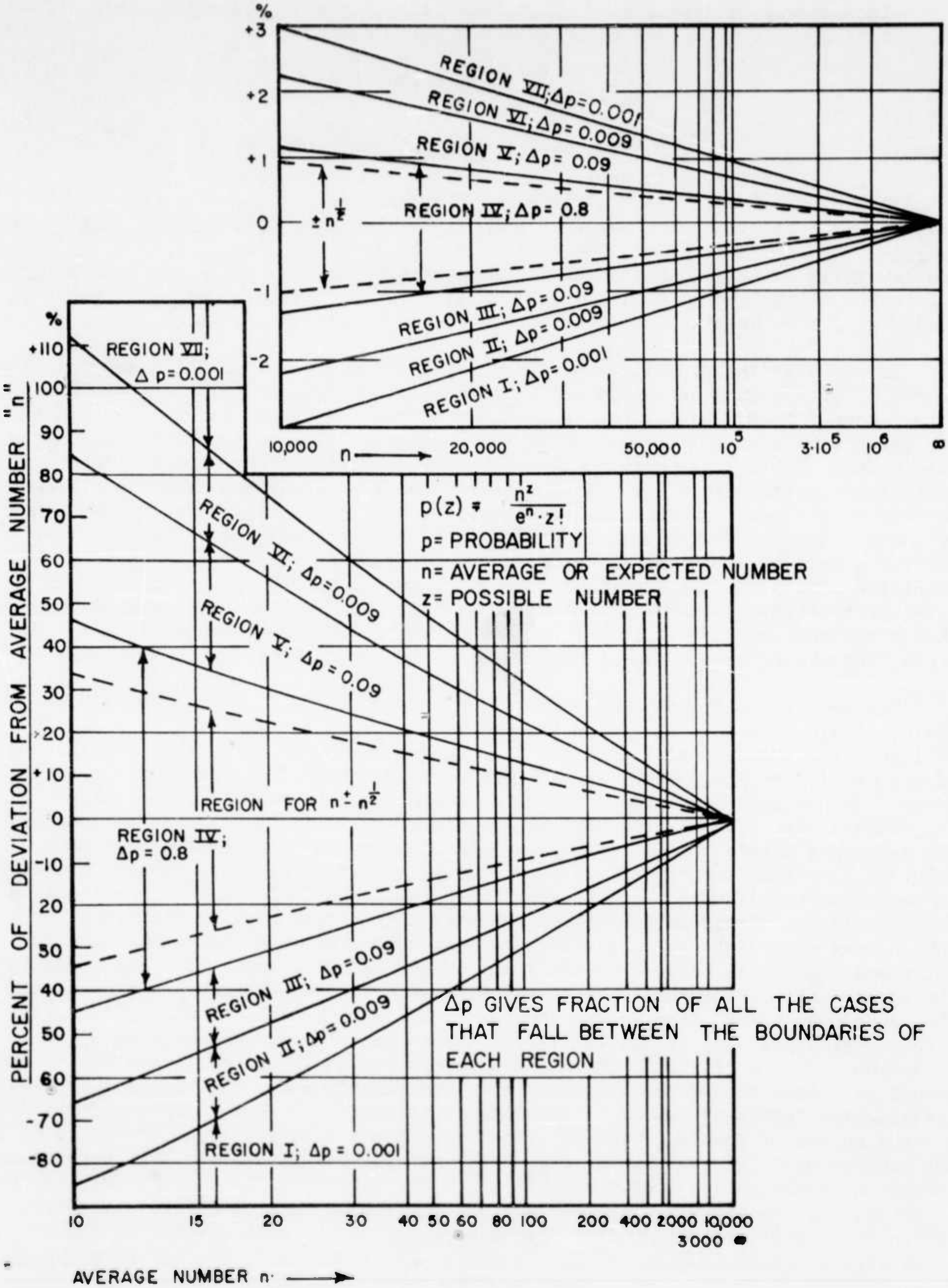

Figure 4. Deviation from Average Number "n" of Poisson Distribution

Since energy is quantitized and because the quanta of radiation coming from any emitting source are emitted at a random rate, a fundamental limit to detection of a celestial body against the background, by any means, is based on statistical considerations. A photographic emulsion having a quantum efficiency of one (where one grain which can be counted, observed, or used for reproduction of the stored information has been developed for each quantum of light striking the photographic emulsion), would contain all the information available; and if all the developed grains in each differential area of the emulsion could be counted, the best possible information on the distribution of brightness in the scene being photographed would be obtained. However, when light strikes a conventional photographic emulsion an average of about 1000 quanta of visible light are required to activate one crystallite, which can then be developed into a grain. Since the process of conversion of the energy of the quanta of light into "developed grains" occurs in a random way, more precise determinations are made by statistical mathematics.

To say that the distribution of developed grains is random is to say that the number of grains in equal small areas of the photographic emulsion varies in a random manner from area to area, and also that the number of grains developed in any given area during different times but with equal time intervals varies in the same manner. It is customary to assume that such random events are governed by the Poisson distribution law. The probabilities for deviations from the average number of developed grains of all the small resolution elements involved as found by the Poisson Law are shown in Figure 4 (Ref. 2). For many practical purposes and for simple calculations it is often assumed that numbers outside certain specified limits (L_1 , L_2) occur infrequently enough to be neglected, and that equal probabilities exist for the n[illegible]rs inside these limits. These specified limits are customarily obtained fr[illegible] average number by adding to it, plus or minus, the square root of the number.

The ability to detect a celestial body depends on the number of usable grains developed within the image area of the photographic emulsion as a result of light from the celestial body and the background combined, and the average number developed in all other equal areas as a result of the background light alone. If one assumes an ideal homogeneous photographic emulsion, then the theoretical limit in detecting brightness differences will be reached by counting the developed usable grains in the area occupied by the image of the celestial body and comparing the result with the average number of developed usable grains in the other equal areas over the rest of the emulsion (Ref. 7). We shall assume arbitrarily as "threshold for detection" that a celestial body must provide enough quanta of light to enable the smallest number of developed usable grains for resolution areas covered by the image of the celestial body to equal or exceed the upper limit of the number of developed usable grains of the areas exposed to the background only. Then we can compute from Figure 4 that the number of developed usable grains produced by the light from the celestial body necessary to achieve detection is not a "fixed fraction" from developed usable grains caused by the background, and that therefore the probability for detection may be increased by increasing the "average" number of developed usable grains. For example, if the average number of usable grains developed for each resolution area corresponding to the background is 25, the number of usable grains lying within the limits for these background areas ranges from the lower limit to the higher limit of $25 \pm\sqrt{25}$ or from 20 to 30; if the light from the celestial body should fall on a resolution area having the lower limit of 20 developed usable grains, it must develop at least 10 additional usable grains because it must reach the upper limit of the background

(30 usable grains) which in this paper is arbitrarily defined as "threshold". The 10 usable grains from the light from the celestial body would then be the lower limit for the light from the celestial body, or in other words, the average of the number, n_s, of usable grains developed by the light from the celestial body, under the previous arbitrary assumptions would be

$$\begin{aligned} n_s &= n_{b\,max} + \sqrt{n_s} \\ &= 10 + \sqrt{n_s} \\ &\approx 14, \end{aligned}$$

and the ratio of the average number of usable grains from one resolution area produced from the radiation of the celestial body to one resolution area produced from the radiation of the background would be 14:25 or the difference in apparent magnitude

$$\begin{aligned} M &= \log \frac{25}{14} \Big/ \log 2.512 \\ &= \log 1.78 \,/\, 0.4 \\ &= 0.6 \end{aligned}$$

If, for example, 100 times more usable grains are now developed for each background resolution area, the range of the number of usable grains is $2500 \pm \sqrt{2500} =$ 2450 to 2550 and the minimum number of usable grains developed by the light from the celestial body must be equal to the difference between the defined limits (L_1, L_2) or 100. The average number of usable grains developed by the light from the celestial body then is $n'_s = 100 + \sqrt{n'_s} = 111$ usable grains. Now we have a ratio of 111:2500 or the difference in apparent magnitude between celestial body and background given by

$$\begin{aligned} M &= \log \frac{2500}{111} \Big/ 0.4 \\ &= 3.4 \end{aligned}$$

While the increase in the ability to detect small differences in brightness that is indicated by this calculation will prove useful later on in this report, it is not easily applicable to photographic emulsions.

Obviously, it is desirable to increase the number of developed usable grains as much as possible. This may be achieved by increasing the exposure time, or by increasing the telescope objective diameter, or by increasing the quantum efficiency of the photographic emulsion. However, there is a practical limit to the length of time the telescope can perform perfect tracking, to the diameter of a telescope objective, and to the quantum efficiency of a photographic emulsion. There is also an overriding practical limit to the number of useful grains that can be developed, since if there are too many, transparency is lost, and with it sensitivity to additional exposure. Further, the most sensitive conventional photographic emulsions have the largest grain size. Ultra-fast photographic emulsions, with a speed of 3000 ASA units, have grains with an average projected diameter of approximately 5μ. emulsions used for nuclear work approximately 0.2μ and microfilm as little as 0.3μ.

The microfilm has a speed of only 0.025 ASA. Thus, for conventional photographic emulsion, the speed is roughly proportional to the average projected areas of the grain, but the quantum efficiency, which is the reciprocal of the average number of quanta of light necessary to cause development of one usable grain, is substantially constant.

Some of the information stored in a photographic recording that is detectable by a grain counting device cannot be sensed by the unaided human eye. However, such an ideal grain counting device cannot be employed to the limit determined by statistics as explained in the above, because of serious inhomogeneities in photographic emulsion, and other factors affecting the true random distribution of the grains. The practical value for the smallest brightness difference which can be visually detected is a multiple of the value which could be detected with a grain counting device. Hence, in the search for a celestial body in the presence of a radiant background for direct visual observation the photographic emulsion may be exposed until the most favorable point of the exposure curve is reached for visual detection of the smallest brightness difference; further exposure is useless, because it only leads to over exposure and if all grains are activated, brightness differences can no longer be detected. The equation used for photography therefore contains a factor "r" expressing the minimum of the ratio of light from the celestial body to background radiation necessary for detection, rather than factors relating to statistics of the grains. This factor has to be determined individually for each type of photographic emulsion. The coarse grained photographic emulsions used in astronomy normally require a ratio "r" varying from 1:6 to 1:10. Basic equations and equations relating to photography are included in the appendix.

By direct substitution in the basic Eq (1) we can examine the actual rate of arrival of quanta at the focal plane of the Mt. Palomar 200-inch telescope for which we will assume a transmission efficiency of 0.5. There the background radiation corresponds to the light from a star of the twenty-second apparent magnitude, so that

$$Q_b = \frac{2.13 \cdot 10^4}{2.512^{22}} \cdot 5080^2 \cdot 0.5$$

$$= 435 \text{ quanta / sec}$$

Taking the ratio r as 1/6, the rate of arrival of quanta of light from the faintest detectable celestial body is about 67 per second, the apparent magnitude being about 24. (Ref. 9).

IMAGE-CONVERTER SYSTEM

When using an image-converter system (Figure 2), the quanta of light from the celestial body and from the background, which are focused on the photocathode, are amplified by the same factor. Therefore, the ratio of brightness of the celestial body and background areas is not changed at the reproducing phosphor screen. However in photographing the image, the most favorable point on the exposure curve of the photographic emulsion can be reached in a fraction of the time that would be required in conventional photography. Unfortunately, even when the photocathode of the image converter tube is not exposed to light, it emits a feeble flow of electrons called the dark current. When the image converter tube is in use, these electrons combine with those produced by the image focused on the photocathode and produce additional background at the reproducing phosphor screen. This dark current

can be greatly reduced by cooling the tube. Since the ratio of luminescence between the celestial body and background brightness is not changed, for large telescopes of great light-gathering power, where it can be safely assumed that the flux of light is sufficient to prevent failure of the photographic reciprocity law, and all the time needed for conventional photography is available, faint celestial bodies comparable in brightness to the background can be photographed as well without the uncooled image converter tube as with it, provided the same photographic emulsion is used.

The advantages of the image converter consist in the greatly increased brightness of the image focused on the photographic emulsion and the resultant shorter exposure time required for any given photograph. This can be important where the intensity of the light without the image converter would be so low as to reduce the efficiency of the photographic emulsion because of the failure of photographic reciprocity and the exposure time too long to permit accurate following of the celestial object. Thus, the image converter will make some photographs possible that were not possible previously, and will allow use of a small telescope for some photographs that would otherwise require a large one. Also, finer grained photographic emulsions can be used if the image converter system has sufficient resolution. The finer grained photographic emulsions normally require longer exposure times to attain the same density but they can show more detail and smaller differences in local density variations. Thus, the gain in the image-converter tube makes it possible to use reasonable exposure times with the finer grained photographic emulsions. The shorter exposure times may be very important for tracking purposes. In addition, methods using grain counting techniques, as described above for conventional photography can provide more information when used with the finer grained photographic emulsions.

TELEVISION TYPE OPTICAL AMPLIFIERS

In the study of the type of optical amplifier which utilizes the closed-circuit television principle we find that the extreme flexibility of electronic circuits permits alteration of the final image in a number of ways. For this analysis we shall use these circuits simply to suppress a constant amount of background from the entire picture (Figure 5) (Ref. 12). Figure 5a shows the intensity variations of the stored charge pattern as seen by the scanning beam that moves across the target plate. An average intensity is present in the area corresponding to the background, a larger average intensity in the area corresponding to the image of the celestial body, and random fluctuations are present in both cases. Suppressing electronically a constant amount of the background portion of the signal produces the result shown in Figure 5b, which leaves essentially only the fluctuetions in the background area of the signal. The portion of the video signal caused by the celestial body with fluctuations caused by background and celestial body radiation super-imposed remains. It is also possible, by additional electronic modifications of the video signal, to partially suppress the fluctuations in the background and celestial object areas of the signal (Figures 5c and 5d). Figure 6a shows Jupiter and four moons, with background fluctuations present corresponding to Figure 5c. Figure 6b, again Jupiter and four moons, shows a more complete electronic suppression of the background portion of the signal and the fluctuations corresponding to Figure 5d. Figure 5a would have a different appearance in the actual photographing of a very faint celestial object, whose intensity is comparable to that of the background radiation. The difference in the average densities of the celestial object area of the signal and of the back-

In view of statistical considerations explained in the section "The Photographic System" the theoretical threshold for detection with television type system quite often uses an arbitrary value for $r' = 2$.

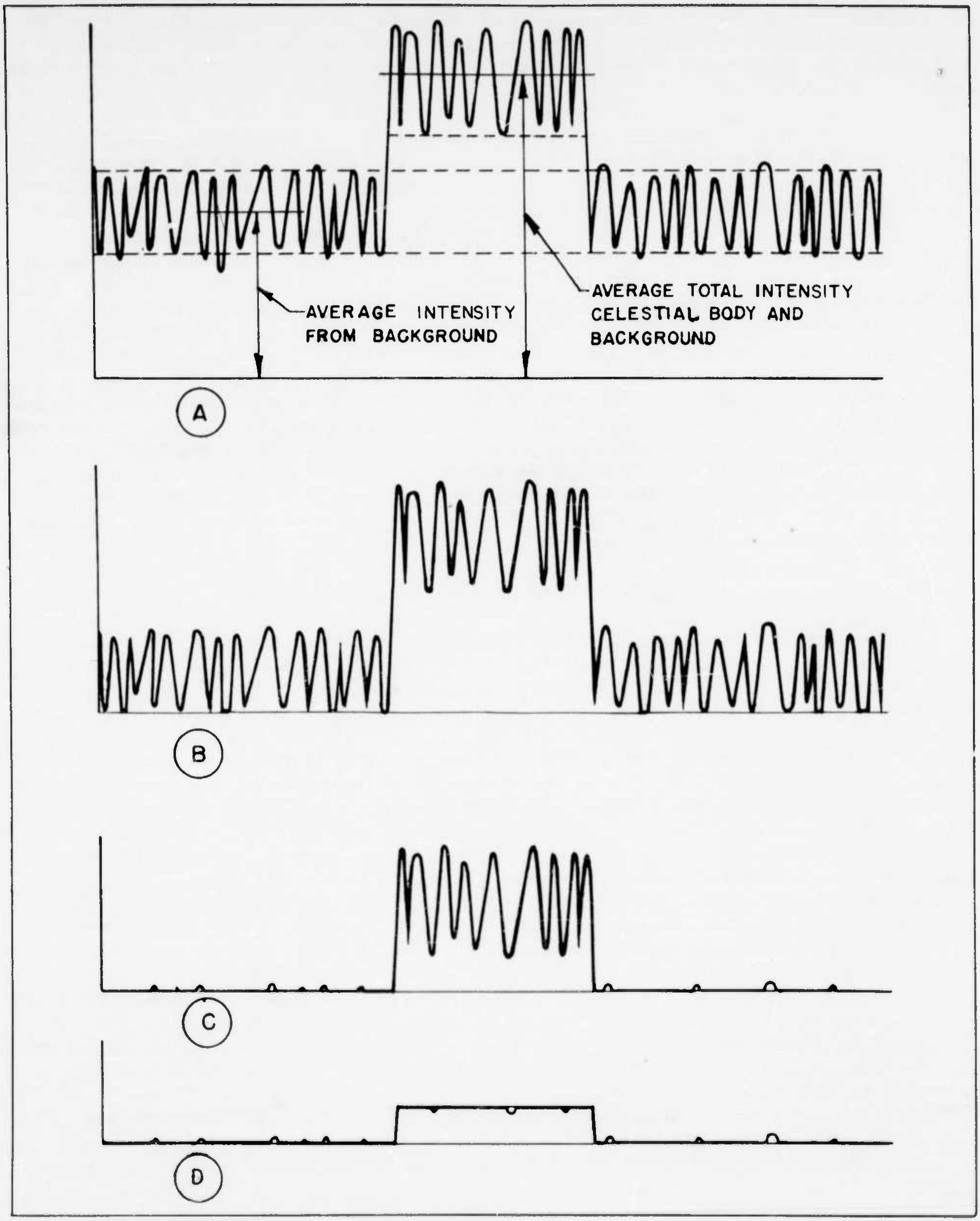

Figure 5. Video Signal Showing Successive Modifications Achieved by Electronic Circuits as shown in Figure 3

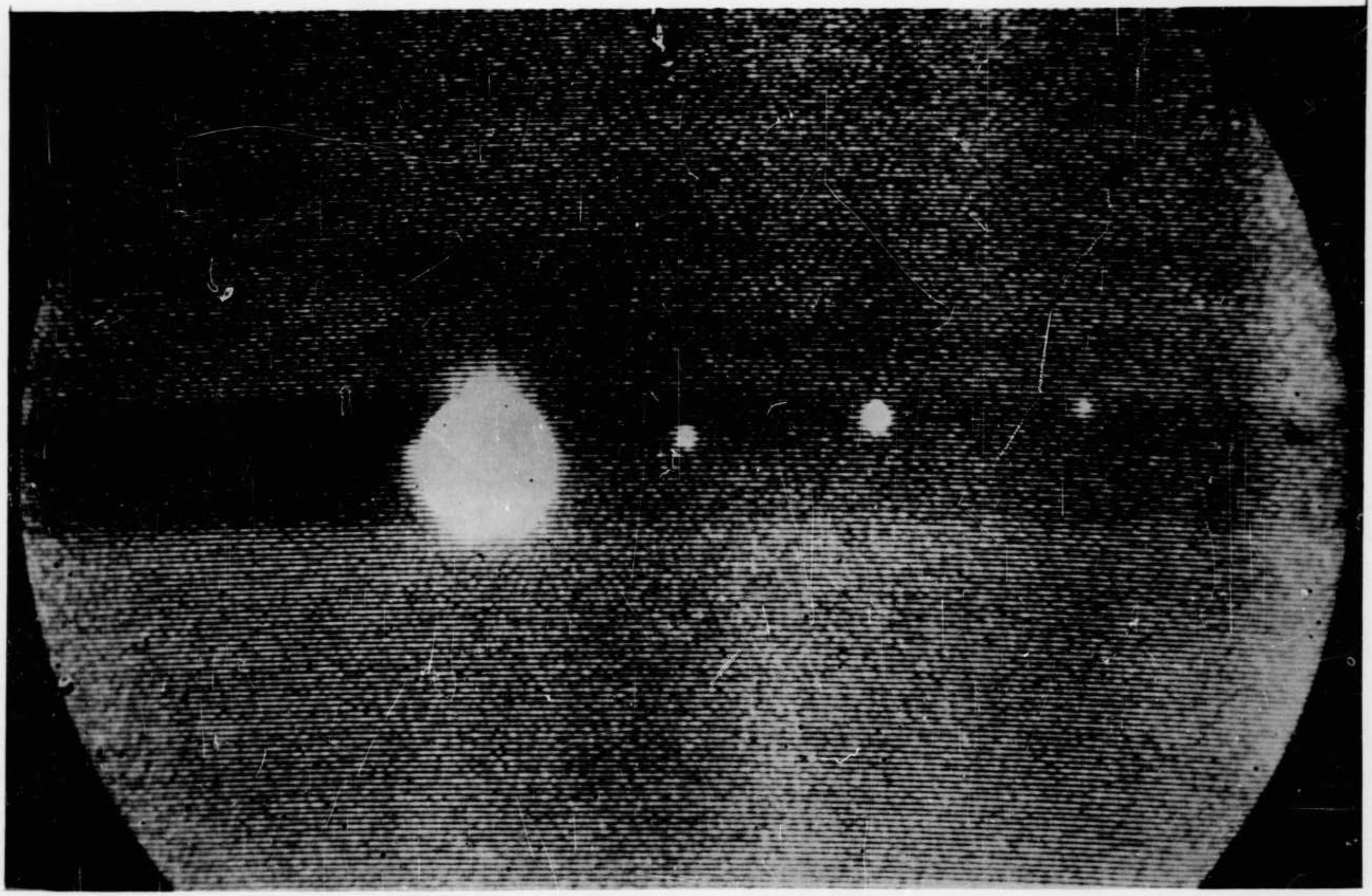

Figure 6a. Jupiter and Four Moons, Taken at Wittenberg with a Television Type Recording System in 1/25 Sec., Showing Effects of Background Fluctuations

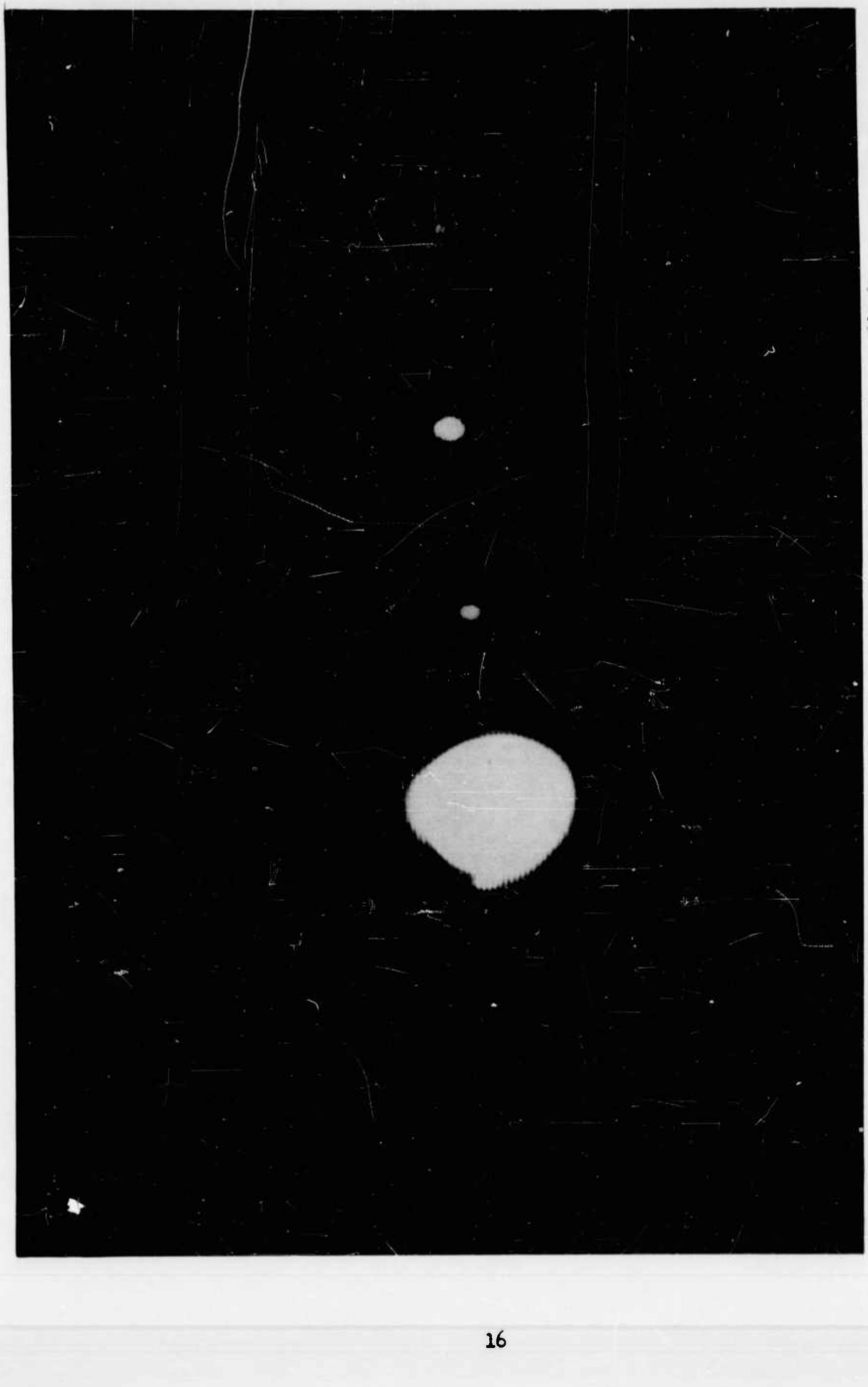

Figure 6b. Jupiter and Four Moons, 1/25 Sec. Exposure Time Showing a More Complete Electronic Suppression of the Fluctuations Shown in Fig. 6a.

ground area of the signal would then be small. However, this does not affect the principle involved in suppression of background from the signal. Since, as explained in the section, "The Photographic System", the percent of deviation from the average number of statistical fluctuations increases as the numbers involved decrease, our concern is not the number of quanta of light arriving at the photocathode but the number of electrons leaving it, which is far smaller. An equation for determining the basic situation for a photo emitter (Eq 2AM) is obtained from Eq (2P) by multiplying Eq (2P) with the conversion efficiency of the photocathode. To write the equation for a minimum number of electrons needed for detection analogous to Eq (3P), two changes are required in addition to this multiplication. First, we have to add the number of dark current electrons per sec per mm^2 (Eq 3AM) to the number of electrons produced by the arrival of background radiation. Second, since the constant portion of the signal corresponding to the background has been subtracted electronically, only the deviations remain. In quantum theory calculations, all absorption and emission processes are assumed to occur at random, and it is customary to assume that the maximum significant deviation from an average is the square root of that average. This introduces an exponent 1/2 in the equation expressing the minimum number of electrons caused by the radiation from the celestial object that are detectable in the presence of electrons caused by the background radiation and dark current.

The mathematical treatment involves an approximation by neglecting the initial fluctuations of light itself and the fluctuations in the photocathode emission and in the combined treatment of the photocathode emission, caused by the arrival of quanta of light from the background and dark current emission; however, these do not affect the general validity of the sensitivity equation.

Using the same procedure as in the photographic case, we may combine this equation with Eq (2AM) to obtain Eq (4AM), which gives the magnitude of a celestial body that is just detectable by the optical amplifier making the same arbitrary assumption for threshold as defined for a photographic grain counting device. In analogy with the photographic case, the equation for the factors A_2 and A_3 of Eq (4AM) contains only constants related to the optical system and r'. In this case r' is the ratio between the average numbers of electrons caused by the radiation from the celestial body and the square root of the average number of electrons corresponding to sky background radiation plus dark current, and the probability of detection of the celestial body is a function of r'.

In view of statistical considerations explained in the section "The Photographic System" the theoretical threshold for detection with a television type system quite often uses an arbitrary value for $r' = 2$.

DISCUSSION

Equation (4AM) contains the factor I, representing the dark current of the photocathode, which impairs the contrast detectivity of the system, and, therefore, decreases the apparent magnitude of the celestial object that can be detected. Aside from this, there are differences between Eq (4AM) and Eq (4P), which deserve comment.

One of the differences is between the definitions of r and r'. It should be noted that, in the conversion of quanta of light to latent grains in the photographic emulsion, the conversion efficiency is so low as to make the statistical

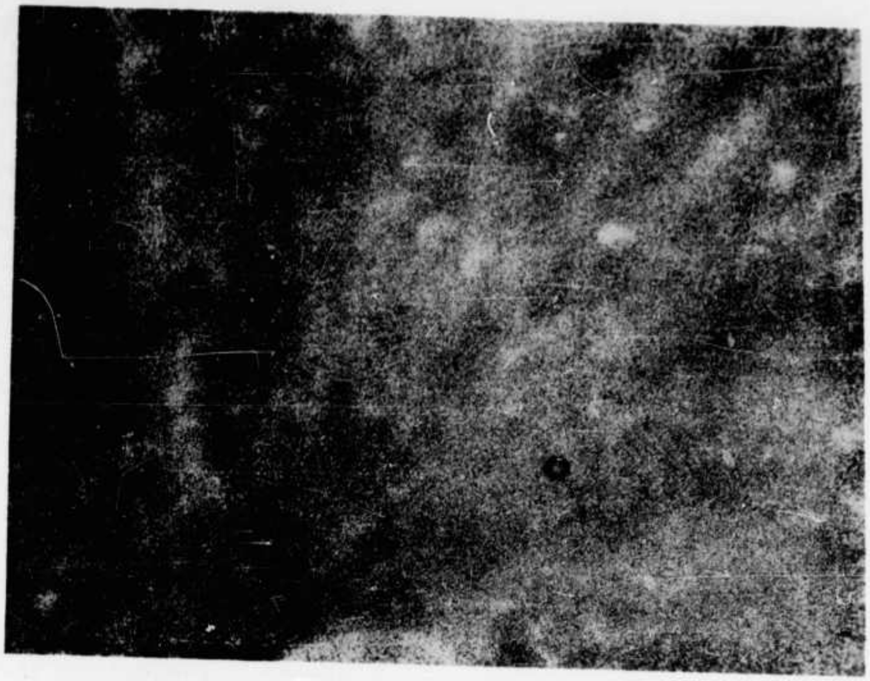

Figure 7. Conventional Photograph of an Area of the Moon, Near Tycho, Using an Aperature of 25 cm, Effective Focal Length of 15 Meters Taken During Full Moon

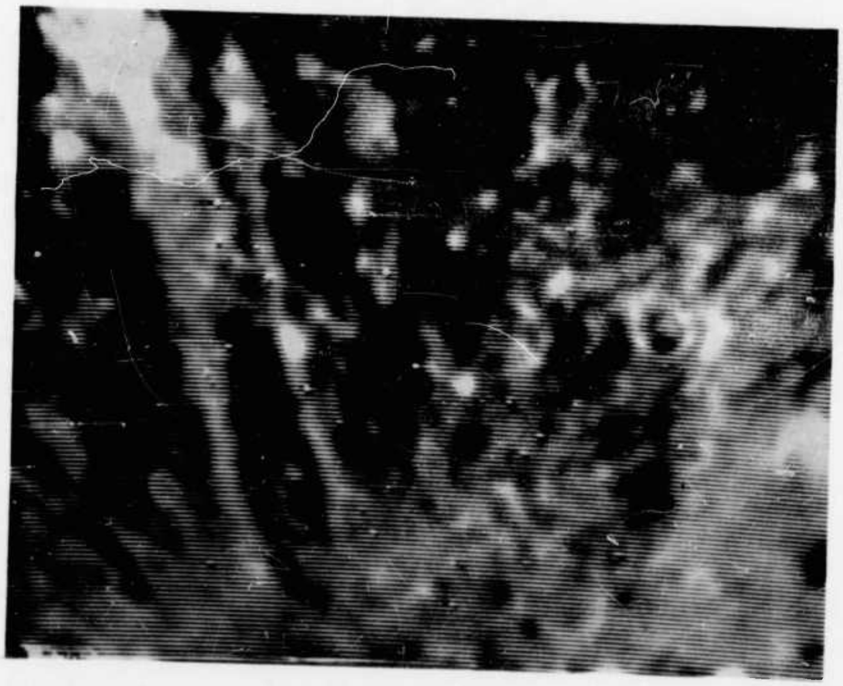

Figure 8. Same Section of the Moon as in Figure 7 Taken from the Cathode Ray Tube of a Closed Circuit Television System Using the Same Optics

fluctuations in the incident quanta arriving from the celestial body of minor importance. Rather, the statistical fluctuations in the conversions of the energy are dominant. Theoretically, r for an ideal homogeneous photographic emulsion can be decreased indefinitely by increasing the number of developed useful grains and, instead of depending on the density of the developed emulsion for obtaining the recorded information, an electronic device is used for counting the useful grains and a computer for interpreting the results. However, in view of the low efficiency of the photographic emulsion in translating quanta of light into developed usable grains, such complicated instrumentation may not be justifiable.

When an image converter arrangement is added to the conventional photographic system the difference in brightness that can be discriminated in the photographic record can never be smaller than as determined by the irregular statistical variations occuring in the conversion process of the light into developed useful grains i. e., as determined by the total number of developed useful grains per resolution element. However, if sufficient intensification is used the irregular statistical variations in the number of electrons released from the primary photocathode of the image converter may become the dominant factor for contrast detectivity, since the percentage of the statistical variations is largest for the smallest number involved. For detecting the smallest contrast and for optimum utilization of the number of useful grains available on a photographic emulsion used for recordings with an image converter system, the chosen gain in lightflux should permit just one photoelectron from the primary photocathode of the image converter system to produce one useful grain in the developed photographic emulsion. If the gain is increased beyond this situation so that many useful grains are developed for each photoelectron the photographic emulsion will be saturated in less time than is the case with the lesser intensification, therefore restricting the total number of photoelectrons to a lesser number and increasing the percentage of their statistical variations.

By using the intensifier image orthicon pick-up tubes, television type light amplifier chains are capable of presenting on a cathode ray tube screen the irregular statistical variations of the photocathode dark current or the randomness of the photo emission caused by a low level light scene. This is accomplished by suppressing electronically the average value of the dark current or of the emission caused by the low level light scene. When obtaining photographic recordings, using a television type of light amplifier and employing intensifier tubes, the limit in detecting brightness differences no longer depends on the number of useful grains available at the photographic emulsion or the homogeneity of the emulsion, but in the statistical fluctuations of the photoelectrons emitted by the photocathode. The contrast in the reproduced scene can be increased to the point where even very coarse photographic emulsions are sufficient for the final recording of differences in scene brightness which are very close to the limit of detection determined by statistics. This is illustrated by comparative photographs. Figure 7 shows a section of the moon recorded by conventional photography and Figure 8 of the same section shows a very strong increase in contrast. Figure 8 was photographed from the cathode ray tube of a television type light amplifier. Both pictures were taken using the Weaver Observatory telescope with a 25 cm aperture and an effective focal length of 15 meters at Wittenberg University, Springfield, Ohio.

The limiting capabilities in detection of differences in brightness of a photographic recording depend on the number of usable grains available, and of a television type amplifier on the number of elementary charges that can be stored on the target plate. Therefore, in the following procedure for making a correct

comparison between the two systems, the approximate number of elementary charges than can be stored on a storage target plate of a television type amplifier is calculated and compared with the number of usable grains available in a photographic emulsion.

Assuming no lateral leakage between elements of resolution for the time of storage, the number of elementary charges that can be stored depends on the capacity of the storage target assembly and the voltage which can be built up without discharge by breakdown. In television pick-up tubes two-sided target plates with an area of one square inch are presently used. In the present state-of-the-art a wire mesh may be placed at an effective distance of 10μ from the target plate and a potential of 20 volts can be safely built up. The capacity of such a storage arrangement, neglecting the reduction by the holes in the mesh wire, is approximately given by

$$C = \frac{1.1\,A}{4\,\pi\,d} = \frac{1.1\,(2.54\,\mathrm{cm})^2}{4\,\pi\cdot 10^{-3}\,\mathrm{cm}}$$

$$= 565\ \mu\mu F$$

and the charge in Coulombs which can be stored at 20 volts is

$$CV = 5.65\cdot 10^{-10}\cdot 20$$
$$= 11.3\cdot 10^{-9}$$

One Coulomb = $0.629\cdot 10^{19}$ elementary charges; the charge then contains $11.3\cdot 10^{-9}\cdot 0.629\cdot 10^{19} = 7.1\cdot 10^{10}$ elementary charges. Assuming $315 \times 315 = 10^5$ points of resolution on the target plate we have for each point of resolution $7.1\cdot 10^{10}/10^5 = 7.1\cdot 10^5$.

Then, if we assume no multiplication of the number of electrons between photocathode and storage plate for achieving optimum storage utilization but neglect the small deviations due to randomness in the number of additional electrons caused by the radiation from a celestial body, the deviation, computed by similar assumptions as in the section "The Photographic System", is $(7.1\cdot 10^5)^{1/2} = 840$ and the ratio between the intensity of radiation from a celestial body and the background when $r' = 2$ is

$$2\cdot\frac{8.4\cdot 10^2}{7.1\cdot 10^5} = 1:433\ ;$$

this corresponds to ≈ 6.6 apparent magnitudes and represents the number of apparent magnitudes by which the celestial body could be fainter than the background. The size of the resolution element chosen in the above example was 0.08 x 0.08 mm, and the photographic emulsions usually employed for astronomical work have grains with an average projected diameter of 2μ and could have a maximum of 40 x 40 non-overlapping grains in such an area. Following the procedure above gives a ratio of

$$\frac{2\cdot 40}{1600} = 1:20$$

In this case the celestial body could be 3.3 apparent magnitudes fainter than the background. So, compared with the 6.6 apparent magnitudes above, we could detect a celestial body 3.3 apparent magnitudes fainter with the television type of optical amplifier. Also, through the quantum efficiency of the photocathode as compared with the 0.1 percent of the photographic emulsion, the conversion of the energy may be 100 times as efficient. The capacity of the storage target assembly may be increased by using a metal mesh wire screen as carrier for the storage plate, or the two sided storage plate may be replaced by two parallel plates with an insulator between them having a high dielectric constant. In this case the scanning by the electron beam must be performed on the same side of the assembly the primary electrons from the photocathode are focused on. With modern materials available the capacity of such a storage target assembly may be increased more than 10,000 times over the conventional ones. This would make it possible with such a storage target to detect celestial objects an additional 5 apparent magnitudes fainter than with the conventional storage plates, and then, theoretically, stars fainter than the background by 11.5 apparent magnitudes could be detected, assuming that the dark current of the photocathode is not the limiting factor.

CONCLUSION

The limit of the capability to detect differences in brightness (the contrast detectivity) with a conventional photographic system is practically determined by the constants of the optical system and the limiting characteristics of photographic emulsions. Best performance for direct visual observation is obtained by exposing the photographic emulsion just long enough to attain maximum contrast; further exposure results in a loss. When a photographic emulsion is used with an image-converter the recording speed may be increased as much as one-thousand times, but any improvement of the contrast detectivity is due to the fact it becomes possible to use finer grained emulsions (generally unsuitable because of their slow speed), rather than due to the image converter tube itself since the tube does not effectively enhance the contrast. If the image converter tube is not cooled, the dark current from the photocathode, which acts as additional background, may even seriously reduce the contrast. On the contrary, an optical amplifier working on closed-circuit television principles because of the possible modifications of the electronic signal, can increase the speed of recording several thousand times; its contrast detectivity is limited mostly by statistical fluctuations in the number of electrons emitted, both as dark current and as image current, by the photocathode of the intensifier image orthicon. The ability of this system to detect faint objects against a luminescent background increases with the exposure time because of the larger total number of quanta of light collected. Practically the smallest difference in brightness that can be detected and then visually observed or recorded on any photographic emulsion depends on the amount of the charge which can be stored on the target plate and the length of time that the charge can be held without sufficient change in its distribution, resulting in a noticeable loss of resolution.

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(over)

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